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CORNELL UNIVERSITY

Center for Radiophysics and Space Research

ITHACA, N. Y.

SEMI-ANNUAL STATUS REPORT

to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

under

NASA Grant NAGW-116

RADAR INVESTIGATION OF ASTEROIDS

January 1, 1984 - June 30, 1984

Principal Investigator: Professor Steven J. Ostro

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Prepared July 1984

Professor Steven J. Ostro
Principal Investigator

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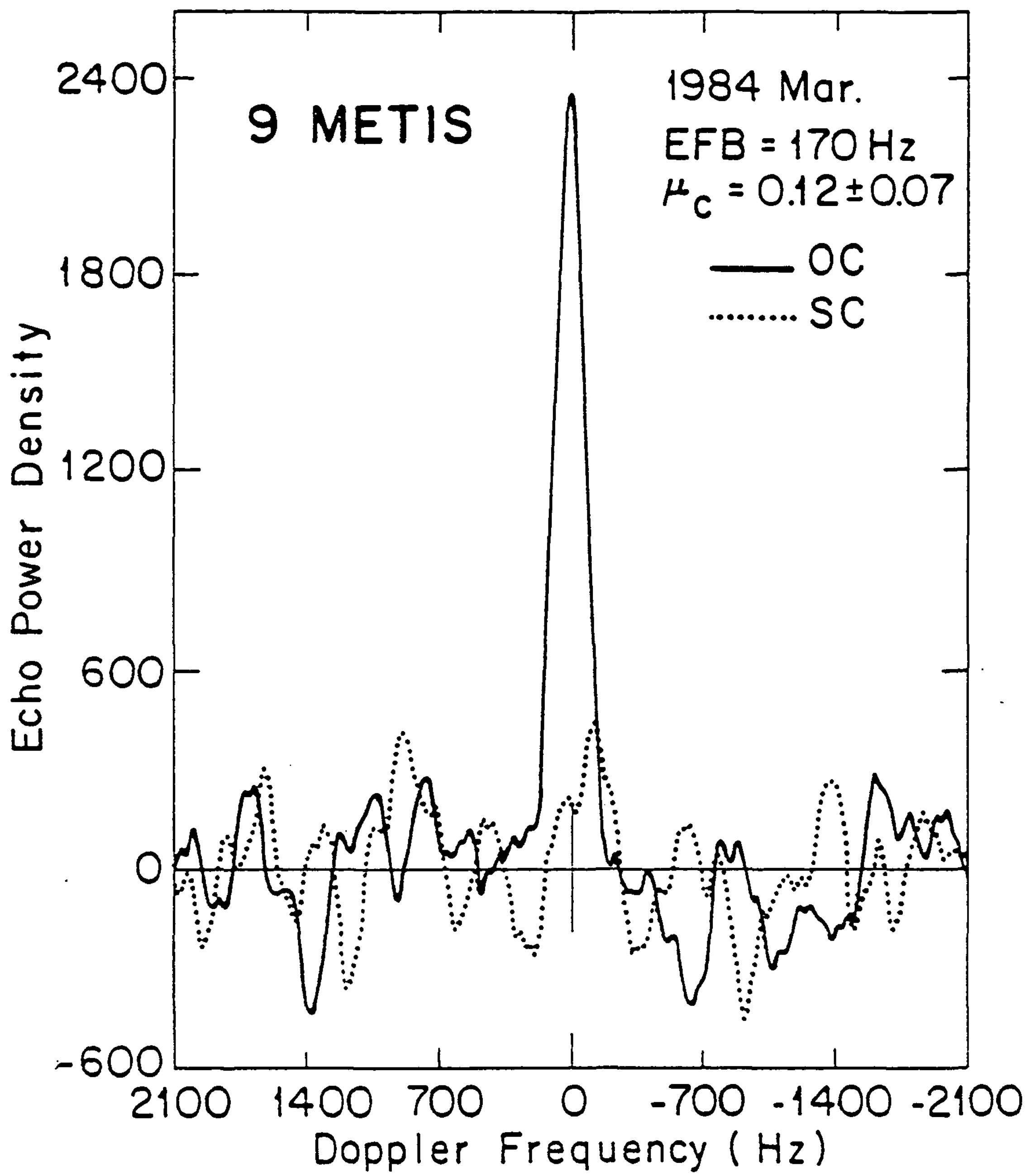
I. SUMMARY OF PROGRESS

During the current report period, research supported under NASA Grant NAGW-116 proceeded as follows:

New Radar Observations

The principal investigator conducted the initial radar observations of the mainbelt asteroids 9 Metis, 27 Euterpe, and 60 Echo. For each target, data were taken simultaneously in the same sense of circular polarization as transmitted (i.e., the "SC" sense) as well as in the opposite (OC) sense. Estimates of the radar cross sections σ_{OC} and σ_{SC} provide estimates of the circular polarization ratio, $\mu_C = \sigma_{SC}/\sigma_{OC}$, and the normalized OC radar cross section, $\hat{\sigma}_{OC} = \sigma_{OC}/A$, with A the target's projected geometric area. As discussed below, $\hat{\sigma}_{OC}$ is expected to be ~ 10% larger than the target's Fresnel, normal-incidence, power reflection coefficient, R. The echo bandwidth is given by $B = (4\pi\ D \cos\ \delta)/\lambda P$, where δ is the asteroid-centered declination of the radar, P is the synodic rotation period, and D is the breadth, measured normal to the line of sight, of the asteroid's polar silhouette.

Figure 1 shows optimally filtered OC and SC echo power spectra for Metis. The circular polarization ratio, $\mu_C = 0.18 \pm 0.08$, is comparable to values measured for other large S-type asteroids (e.g., 5 Astraea and 12 Victoria) and for a few much smaller, Earth-approaching objects (1685 Toro and 2100 Ra-Shalom). For each of these objects, most of the echo is due to single-reflection backscattering from smooth surface elements.



9 METIS
1984 Mar.
EFB = 170 Hz
$\mu_C = 0.12 \pm 0.07$
OC
SC
Echo Power Density
2400
1800
1200
600
0
-600
2100 1400 700 0 -700 -1400 -2100
Doppler Frequency (Hz)

FIGURE 1

One month prior to the radar experiment, a stellar occulation by Metis was observed at several sites in northern Europe (L. Kristensen, private comm.). A preliminary reduction shows a 220 × 180 km profile, whose effective diameter, $(220 \times 180)^{1/2} = 199$ km is 18% larger than the TRIAD value. Combining the occultation and radar data yields a value for Metis' normalized cross section ($\hat{\sigma}_{OC} = 0.08$) that is nearly identical to the lunar value, and an orientational constraint ($\delta = 79° \pm 2°$) corresponding to a nearly pole-on view. The latter result is consistent with the tiny amplitude (<0.05 mag) of Metis' lightcurves during Feb-Mar 1984.

The radar spectra (Fig. 2) show a peculiar surge in echo strength from Metis' receding (negative-Doppler) limb within a certain ~ 30° interval of rotational phase, just past a minimum in optical brightness. This extreme spectral asymmetry is without precedent for planetary radar targets and is especially perplexing given the nearly pole-on view. It might best be explained in terms of a major topographic irregularity on this object.

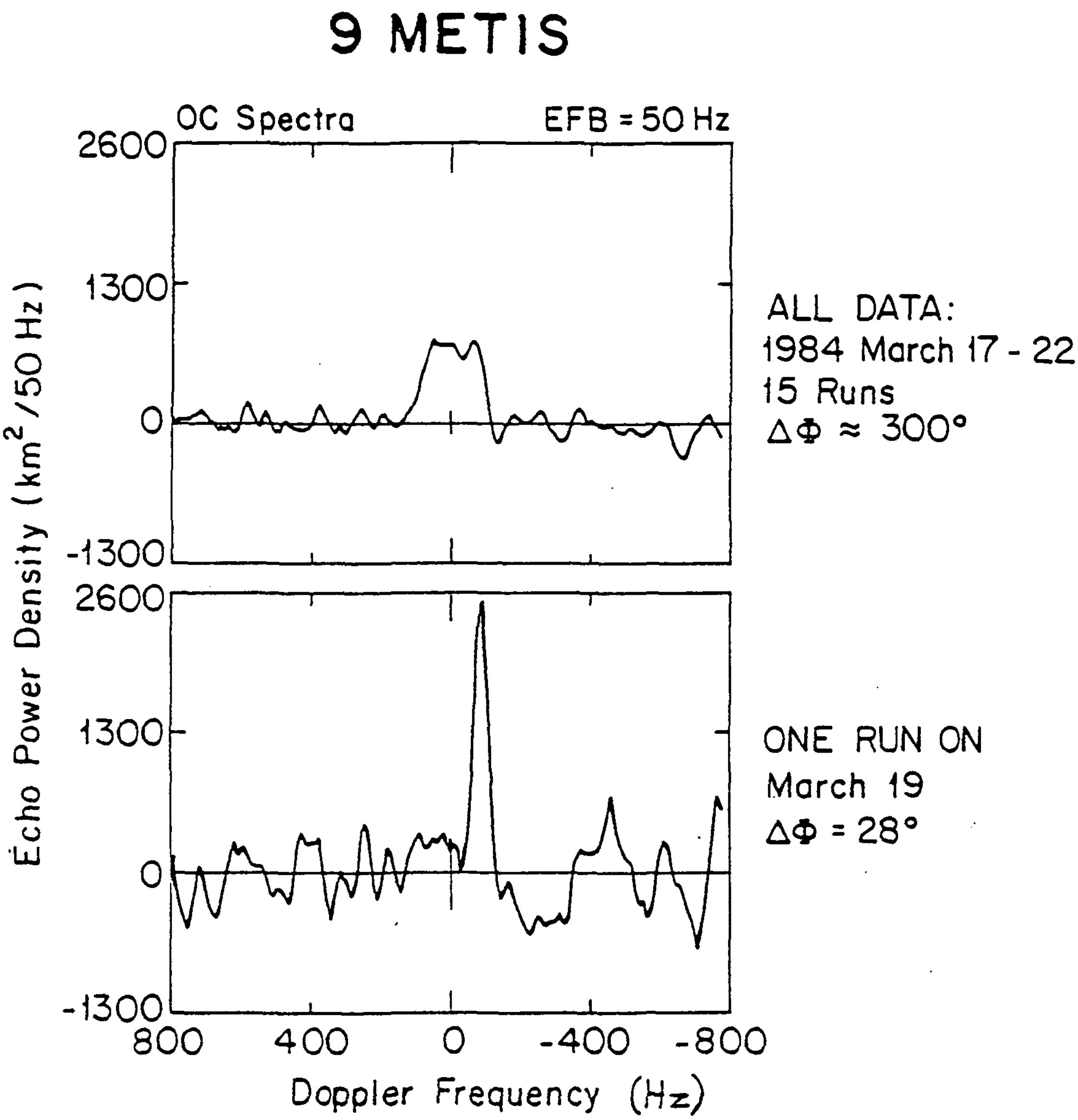

9 METIS
OC Spectra
EFB = 50 Hz
2600
1300
0
-1300
2600
1300
0
-1300
Echo Power Density (km^2/50 Hz)
ALL DATA:
1984 March 17 - 22
15 Runs
ΔΦ ≈ 300°
ONE RUN ON
March 19
ΔΦ = 28°
800
400
0
-400
-800
Doppler Frequency (Hz)

FIGURE 2

Neither 27 Euterpe nor 60 Echo were detected, but the derived upper limits on $\hat{\sigma}_{OC}$ are quite useful. Euterpe is the same taxonomic type (S) and the same 24-color-spectral type (RA-2) as 8 Flora (Gaffey and McCord, 1979). Flora's normalized cross section is $\hat{\sigma}_{OC} = 0.073$, so the Euterpe upper bound (0.12) seems reasonable.

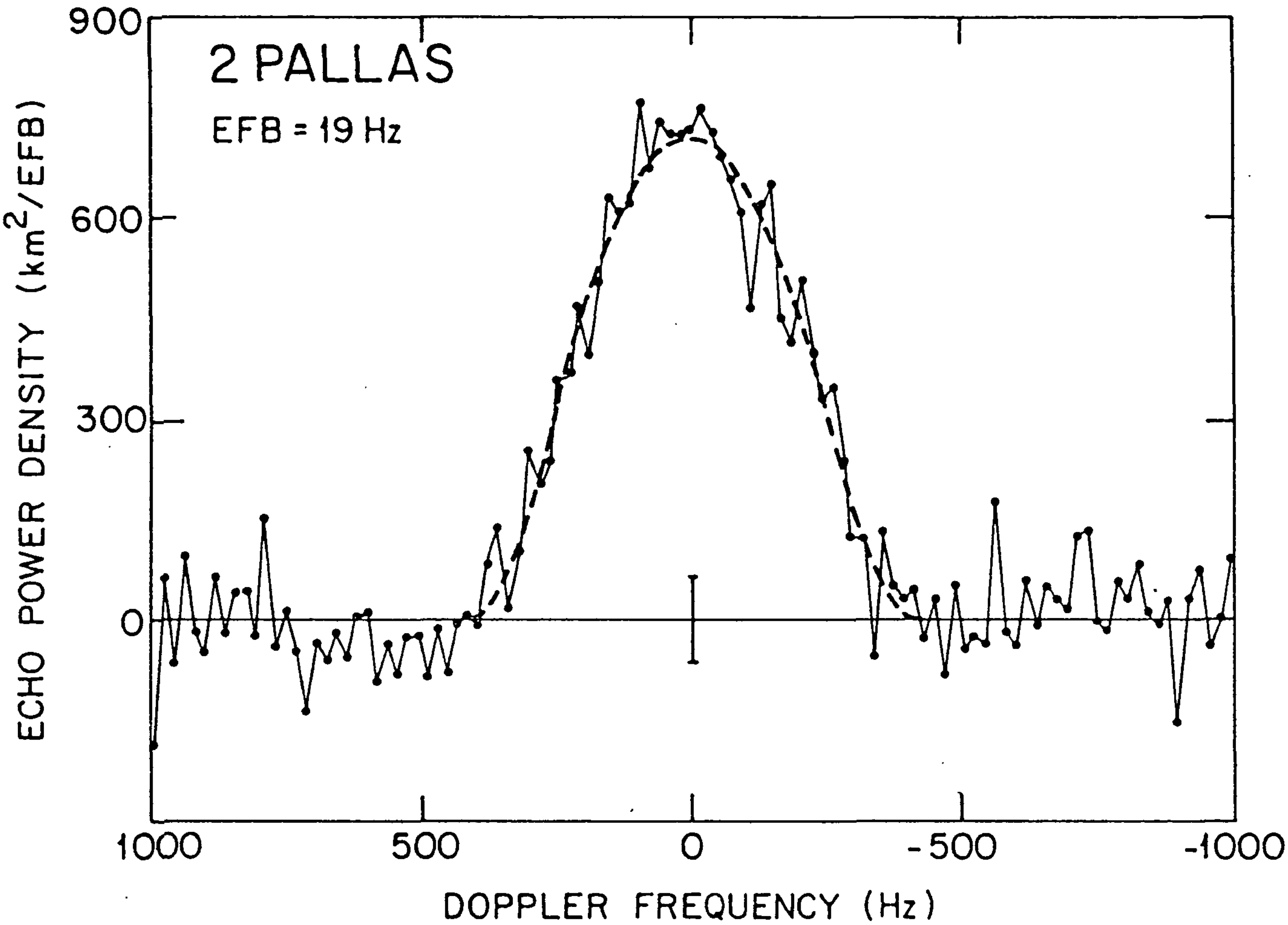
Echo is also an S-type but not an RA-2. Prior to the radar observations, its rotation period P had been thought to be 53.5 h (e.g., Dermott et al., 1984), a rather large value for an asteroid. Radar echo strength is proportional to $P^{1/2}$, and the Arecibo observations should have yielded a detection of 60 Echo unless $\hat{\sigma}_{OC}$ were substantially less than 0.08, or P were substantially less than 53.5 h. The principal investigator communicated this circumstance to several optical astronomers, and subsequent observations (K. Zeigler, private comm.) demonstrated that Echo's spin period actually is 25.21 h, a value that propagates into a more plausible upper bound ($\hat{\sigma}_{OC} < 0.11$) on this object's radar reflectivity.

Highlights of Data Analysis

During the current report period, critical progress was made in physical interpretation of radar echoes from mainbelt asteroids. One of the richest asteroid radar data sets is that obtained two years ago for 2 Pallas, for whom a precise spin period and precise, occultation-derived dimensions lead one to the expression $B = 2000 \cos \delta$ for the bandwidth (in Hertz) of Pallas' weighted-mean echo spectrum (Fig. 3). At the 3-standard-deviation level, $B > 500$ Hz, so $\delta < 75°$ and the radar view was at least ~ 15° from pole-on. However, the data do not in themselves preclude the possibility that $B \approx 2000$ Hz.

If Pallas' angular scattering law $[\sigma_0(\theta)]$ were known, one could formally estimate B, and hence δ. Conversely, if δ and hence B were known, then the spectral shape would be defined and could be inverted to yield $\sigma_0(\theta)$, a function from which one could extract interesting physical properties of the surface (slope statistics and reflection coefficient, R).

Recent analyses of Pallas lightcurves (Binzel, 1984) suggest that $\delta \approx 60° \pm 10°$ during the Pallas radar runs, or $B \approx 1000 \pm 300$ Hz. The dashed curve in Fig. 3 is a model spectrum with B = 1000 Hz and has been derived for a sphere with a scattering law of the form $\sigma_0(\theta) \sim \cos^{-4}\theta \exp(-s_0^{-2}\tan^2\theta)$, where s_0 (radians) is the adirectional rms slope.



2 PALLAS
EFB = 19 Hz
ECHO POWER DENSITY (km²/EFB)
900
600
300
0
1000
500
0
-500
-1000
DOPPLER FREQUENCY (Hz)

FIGURE 3

This law, which assumes that the surface height distribution and lateral autocorrelation functions are Gaussians (Simpson and Tyler, 1982; Beckmann, 1963) rarely matches lunar or inner-planet data, but values of s_0 within ~ 10° of 25° provide statistically acceptable fits to the Pallas spectrum. Such rms slopes are huge compared to typical lunar and inner planet values (0.1° to 10°).

Several arguments support the view that slopes on Pallas have an rms value ~ 25°. Much larger slopes would introduce a multiple-scattering component into the echo, causing a large circular polarization ratio, but Pallas has the lowest value of μ_C (0.05 ± 0.02) measured to date. Much smaller slopes would result in a very sharply peaked echo spectrum. All factors considered, the Gaussian scattering law offers a powerful approach to extracting information about the structure of asteroid surfaces from radar spectra.

Moreover, the Gaussian law might provide an essential key to physical interpretation of radar reflectivities. Normalized radar cross sections ($\hat{\sigma}_{OC}$) of mainbelt asteroids are known to span nearly an order of magnitude (Fig. 4). We can write $\hat{\sigma}_{OC} = gR$, where R is the Fresnel power reflection coefficient for normal incidence, and the backscatter gain <u>g</u> depends on the target's angular scattering law, shape, and orientation. For a smooth sphere, g = 1. For the spherical, quasispecular Moon and inner planets, $g \approx 1 + s_0^2$. Since $s_0 > 10° \approx 0.2$ rad for these targets, their <u>g</u> is within a few percent of unity. For a sphere scattering according to the Gaussian

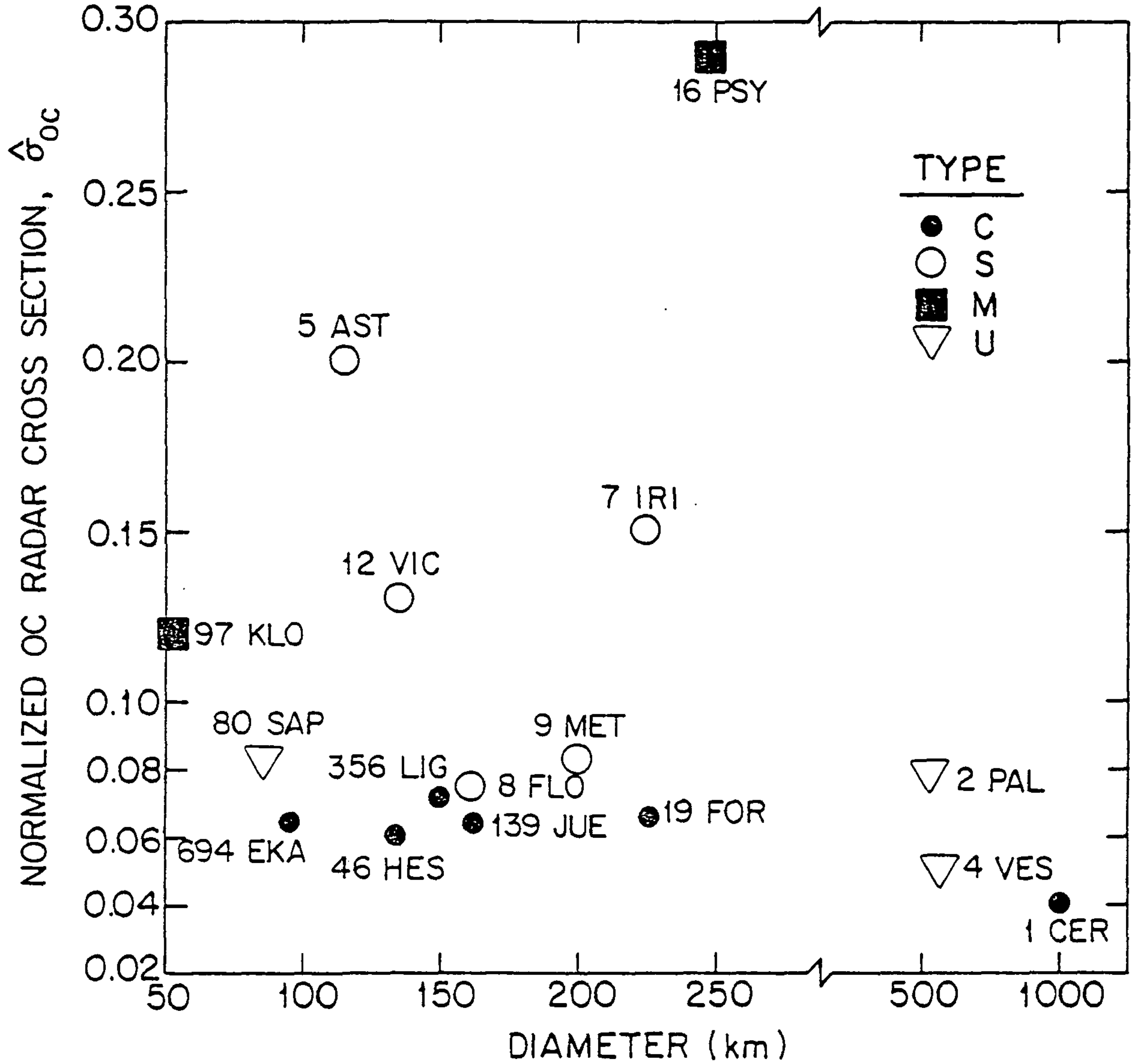

0.30
0.25
0.20
0.15
0.10
0.08
0.06
0.04
0.02
NORMALIZED OC RADAR CROSS SECTION, $\hat{\sigma}_{OC}$
16 PSY
TYPE
C
S
M
U
5 AST
7 IRI
12 VIC
97 KLO
80 SAP
9 MET
356 LIG
8 FLO
2 PAL
19 FOR
139 JUE
694 EKA
46 HES
4 VES
1 CER
50
100
150
200
250
500
1000
DIAMETER (km)

FIGURE 4

law with $s_0 \approx 24°$, $g \approx 1.1$. No rough-surface scattering law proposed so far yields $g > 1.5$ for a sphere. It seems that $\underline{g}$ is unlikely to exceed unity by more than a few tens of percent, so the dispersion in $\hat{\sigma}_{OC}$ is more readily understood as due to variations in R than in $\underline{g}$.

Laboratory measurements carried out by the principal investigator show that for dry particulate mixtures of rock and metal, R depends on bulk density $\underline{d}$, weight fraction $\underline{w}$ of metal, and particle-size distribution. The sensitivity to $\underline{d}$ dwarfs that to $\underline{w}$, so any inference of $\underline{w}$ (and hence of constraints on the mineralogy of asteroid regoliths) depends critically on assumptions about $\underline{d}$ (or equivalently, about porosity). If porosity and particle-size distribution were the same (and within lunar values) for each target, all of the variation in $\hat{\sigma}_{OC}$ would be attributable to large variations in metal weight fraction. This hypothesis is consistent with the apparently greater dependence of $\hat{\sigma}_{OC}$ on taxonomic type than on size (Fig. 4). Depending on the particular particle size distribution, the most radar-reflective targets could have very large values of $\underline{w}$ (> 0.5). Laboratory experiments are being planned to explore the detailed dependence of R on $\underline{d}$, $\underline{w}$, and particle size distribution.

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II. FUNDING STATUS

Spending during the current report period was at the anticipated rate. A physics undergraduate, Anthony Ferro, and an astronomy graduate student, Maren Cooke, have been hired (part-time and full-time, respectively) during the summer to assist the principal investigator with data analysis.

III. PUBLICATION OF RESULTS

A paper, "Radar and Photoelectric Observations of Asteroid 2100 Ra-Shalom," has been accepted for publication in Icarus. A paper, "Radar Observations of Mainbelt Asteroids," is in the rough-draft stage and should be finished sometime this summer.

The principal investigator gave invited colloquia on the research supported under this grant at the University of Arizona in April and at the Jet Propulsion Laboratory in June, and will present an overview of this research (abstract appended) at the annual Meeting of the Meteoritical Society in July.

Abstract of paper accepted for presentation at the 47th Annual Meeting of the Meteoritical Society in Albuquerque, NM, in July 1984.

RADAR INVESTIGATION OF ASTEROIDS; S. J. Ostro, Department of Astronomy, Cornell University, Ithaca, NY 14853

Radar observations can provide useful constraints on an asteroid's size, shape, spin vector, topography, decimeter-scale morphology, density, and composition. Since radar techniques achieve spatial resolution of a planetary target in a manner that is independent of the target's apparent angular size, they provide a powerful ground-based tool for investigating asteroids, which generally remain unresolved by optical telescopes. By virtue of the long wavelengths employed, radar measurements furnish unique information about (i) near-surface structure at scales several orders of magnitude larger than the scales probed optically, but much smaller than typical asteroid dimensions; and (ii) regolith bulk density and metal content (i.e., two parameters that are not well constrained optically.)

An intensive series of asteroid investigations was initiated in 1980, using the Arecibo Observatory's λ13-cm (2380-MHz) radar system. So far, echoes have been detected from a total of 25 asteroids (16 mainbelt objects plus 9 Earth-approachers).

As a class of objects, asteroid echoes lack the sharply peaked spectral signature that dominates echoes from the quasi-specularly scattering bodies (e.g., the Moon). This result indicates that asteroid surfaces are rougher than the Moon at some scale(s) at least as large as a few centimeters.

The particular roughness scale can be constrained by measurements of the circular polarization ratio, μ_C, of echo power received in the same sense of circular polarization as transmitted (i.e., the "SC" sense) to that in the opposite (OC) sense. (For the Moon at λ13 cm, $\mu_C \approx 0.1$) Values of μ_C for individual asteroids range from ~ 0.0 to ~ 0.5; the lowest values require that the echo be due to single reflections from surfaces that are smooth at cm-to-m scales, whereas the highest indicate substantial multiple scattering and/or near-surface roughness. Values of μ_C apparently depend on target size and/or VIS-IR taxon, perhaps reflecting gravitational and/or compositional control of regolith processes. For at least some asteroids, μ_C varies across the disc, indicating heterogeneous near-surface structure.

The radar reflectivities of mainbelt asteroids span nearly an order of magnitude and apparently depend on VIS-IR taxon. This result indicates variations in the bulk densities and/or metal concentrations within the top few meters of these objects' regoliths.

This research was supported by NASA Grant NAGW-116. The Arecibo Observatory is part of NAIC, which is operated by Cornell under contract with NSF and with support from NASA.

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